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Attitude Control for a Meteorological Rocket

by William O. Banks, Capt, USAF

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ABSTRACT

It is considered likely that a meteorological rocket which would have the brief capability of a meteorological satelite will soon be needed. Such a vehicle could be used to test out new ideas and equipment for meteorological satellites and to provide a quick satellite's eye view of a questionable weather area.

It will be necessary for this type of vehicle to contain some type of attitude control. This report describes the factors involved in attitude control and develops a theoretical solution. Various known values are then used with the formulas proposed to demonstrate the feasibility of the solution. It is concluded that the problem could be solved by applying implusive torquing to bring the longitudinal axis of the rocket into correct alignment to produce the desired attitude. The torque could be applied by a cold propellant discharged by a bang-bang servo mechanism.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

J. E. Roberts

J. E. ROBERTS
Major General, USAF
Commander

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ILLUSTRATIONS

SECTION 1 - INTRODUCTION

Meteorological satellites, such as Tiros, are proving invaluable as an eye in the sky to observe general weather patterns; however, small vertical probe rockets, such as Loki and Arcas, are necessary for sampling the atmosphere up to 250,000 ft. It is considered likely that an intermediate rocket (suborbital vehicle) will soon be necessary. Such a vehicle would have the brief capability of a meteorological satellite, but the cost and mobility of a vertical probe.

Two possible uses of such a vehicle would be:

1. It could be used to test out new ideas and equipment for meteorological satellites.

2. It could be used to give a quick, satellite's eye view of a questionable weather area, such as a region where there is an alleged tropical cyclogenesis. An existing satellite might have to make many orbits before it would be in a position that a meteorological rocket could assume almost immediately.

Most of the design of an intermediate vehicle will probably be modifications of larger or smaller types of rockets; however, it will be necessary for the intermediate vehicle to have some means of attitude control. The problem of attitude control for these vehicles will be unique.

The purpose of this report is to present a theoretical solution which can be used as a basis for the development of a low-cost attitude control system. The solution to the problem is approached in the following phases:

1. Describe the attitude control problem.

2. Define a mathematical system and symbology that can be used to solve the problem.

3. State the equations of angular motion for a body in free fall.

4. Develop a solution for the problem.

5. Examine some of the state-of-the-art values to determine if the solution approach is practical.

The solution to the problem of attitude control presented in this report was developed by the author, based on ideas on the general subject initiated by Capt J. H. Jacobsmeyer, USAF, and Dr. R. M. Howe, Professor of Aeronautics and Astronautics, University of Michigan.

SECTION 2 - DESCRIPTION OF THE PROBLEM

A vertical or horizontal attitude is the most likely attitude that the payload would be required to assume. A vertical attitude is defined as an attitude in which the longitudinal axis of the payload is normal to the plane of the horizon. A horizontal attitude is defined as an attitude in which the longitudinal axis of the payload is in a horizontal plane and also in the plane of the trajectory.

In addition, it will probably be necessary to spin the vehicle about its longitudinal axis for reasons of stability. The sensor used in this vehicle will probably be some type of detector such as a radiometer or a camera.

Fig. 1 shows a vertically-oriented payload. If the detector is aimed out of the side of the payload at a constant angle ϕ, and if the trajectory does not carry it significantly downrange, the detector will scan the earth below in nearly a circle. If angle ϕ is allowed to vary uniformly, the scanner will describe a spiral. Since the vehicle's actual trajectory will be a parabola with velocity components in the horizontal and vertical, the resultant detector sweep will be at best a modified prolate cycloid.

Fig. 2 shows the horizontally-oriented payload. In this case, the detector will be aimed normal to the spin axis. Thus the sweep of the detector will be a helix as the vehicle moves downrange. For over half of each revolution, the detector will be directed toward space leaving the useful portion of each sweep to be the horizon-to-horizon scan of the earth. Each successive scan of the earth will be a strip farther downrange. The overlap or gap between successive scans will be determined by the height, downrange velocity component, detector beam width, and spin rate.

The attitude control problem of reaching the horizontal is basically the same as that of reaching the vertical; however, the equipment necessary to reach and hold the horizontal varies from that required to

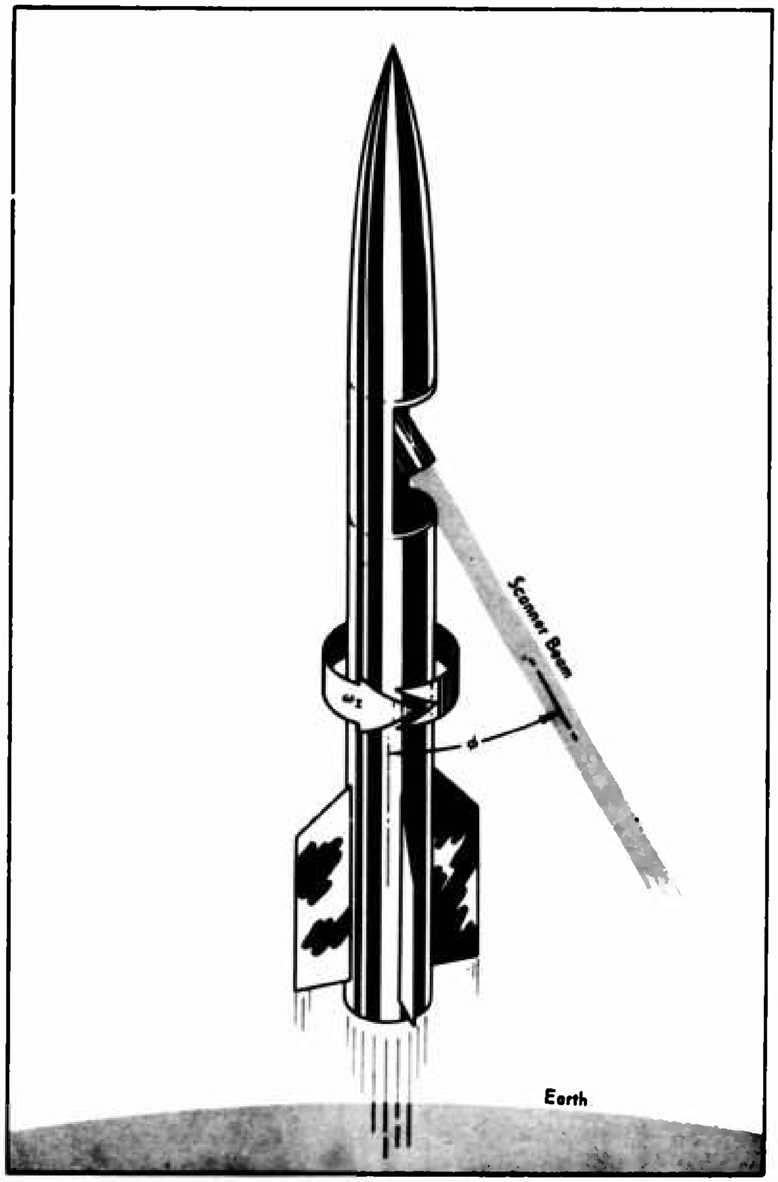

Fig. 1: Vertically-Oriented Payload.

reach and hold the vertical. In reaching the vertical, the horizontal plane can be easily sensed by a spinning radiometer; therefore, if the horizontal plane is known, the payload's vertical is uniquely defined. If a payload were required to assume an attitude other than the vertical, a gyro or celestial navigation system would be required. A difference, then, exists in cost, as a radiometer is inexpensive as compared to a gyro or celestial navigation system.

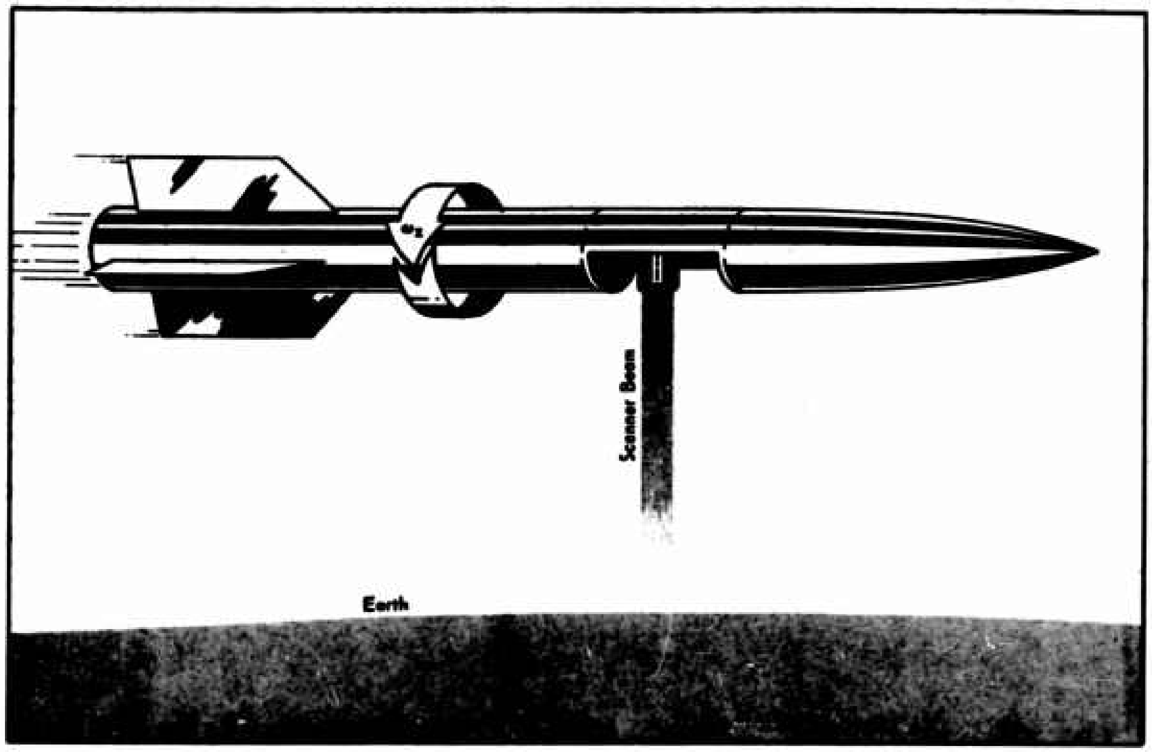

Fig. 2: Horizontally-Oriented Payload.

Since bringing the payload to the horizontal is the more general case, it will be discussed exclusively hereafter.

SECTION 3 - DEFINITION OF TERMS

BODY-FIXED COORDINATE SYSTEM

Most components will be taken in a cartesian, body-fixed, principal axis system using axes which are called x, y, and z (see Fig. 3). The origin is at the center of mass.

z - the axis of mass symmetry of the payload. It is the longitudinal axis.

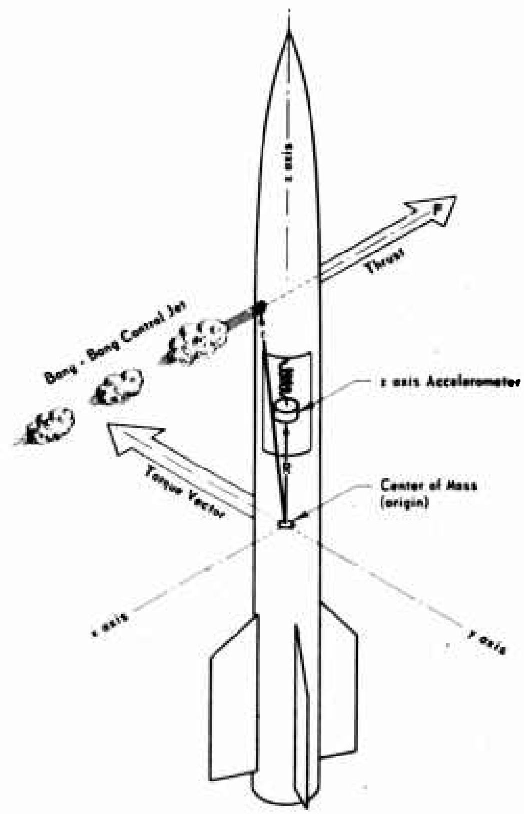

Fig. 3: Body-Fixed Coordinate System.

x and y - the lateral axes passing through the center of mass and rotating with the body.

TRAJECTORY COORDINATES

These axes are determined by the earth and by the trajectory. They also are cartesian but nonrotating. Their origin is also the center of mass, with the axes named u, v, and w (see Fig 4).

u - this axis is horizontal and in the plane of the trajectory. The term horizontal axis will be used in this report to indicate the u axis.

v - the vertical axis is defined as being normal to the horizontal plane.

w - this axis is horizontal but perpendicular to the plane of the trajectory. The term normal axis will be used in this report to indicate the w axis.

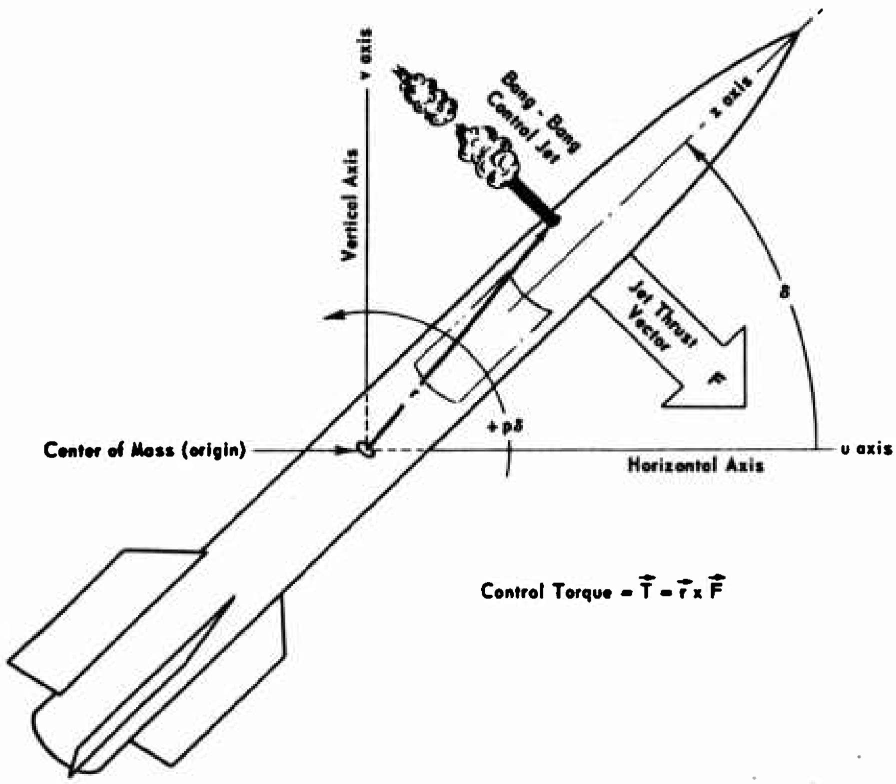

Fig. 4: Trajectory Coordinates.

SUBSCRIPTS

Subscripts will designate along which axis the components are taken.

DIFFERENTIAL OPERATOR

The term p, as used in this report is the same as the time derivative often seen as (d/dt) or ($\dot{}$). The use of p is for simplicity and convenience in converting into Laplace transforms.

For example, pM is identically the same as (dM/dt) or ($\dot{M}$) or the first time derivative of M, while p^2M is the same as (d^2M/dt^2) or ($\ddot{M}$) or the second time derivative of M.

VECTORS

M - the total external moment or torque acting on a body.

H - the total angular momentum of a body.

Ω - the total angular velocity of a body.

R - the position vector from the center of mass to the z axis linear accelerometer.

r - the position vector from the center of mass to the control jet.

a - linear acceleration.

ANGULAR MEASUREMENTS

δ - the angle between the u axis and the z axis.

$-p\delta$ - the closing rate of the u axis and the z axis.

TENSOR

I - the inertia tensor.

COMPONENTS

Since we chose principal axes, the products of inertia in the inertia tensor become zero.

$$I = \begin{bmatrix} I_x & J_{yx} & J_{zx} \\ J_{xy} & I_y & J_{zy} \\ J_{xz} & J_{yz} & I_z \end{bmatrix} = \begin{bmatrix} I_x & O & O \\ O & I_y & O \\ O & O & I_z \end{bmatrix} = \text{diagonal matrix.}$$

Since vectors M, H, and Ω are three dimensional, they are written in matrix form as follows

$$M = \begin{vmatrix} m_x \\ m_y \\ m_z \end{vmatrix}, \qquad H = \begin{vmatrix} h_x \\ h_y \\ h_z \end{vmatrix}, \qquad \Omega = \begin{vmatrix} \omega_x \\ \omega_y \\ \omega_z \end{vmatrix}.$$

ω_{x-y} is the component of Ω in the x-y plane, i. e. $\omega^2_{x-y} = \omega^2_x + \omega^2_y$.

SCALARS

t - time.

k - linear torque coefficient.

f - the viscous damping coefficient.

SECTION 4 - MATHEMATICAL DESCRIPTION

In any body, the sum of the torques equals the rate of change of the angular momentum. The equation is

$$M = pH. \tag{1}$$

Vector equation 1 may be broken up into components. If derivatives are taken in a rotating axis system, there must be coriolis terms, so that equation 1 becomes

$$\begin{aligned} m_x &= ph_x - h_y\omega_z + h_z\omega_y \\ m_y &= ph_y - h_z\omega_x + h_x\omega_z \\ m_z &= ph_z - h_x\omega_y + h_y\omega_x. \end{aligned} \tag{2}$$

The definition of angular momentum is

$$H = I\Omega \tag{3}$$

where H is a column matrix (h_x, h_y, h_z); I is a diagonal matrix (I_x, I_y, I_z); and Ω is a column matrix (ω_x, ω_y, ω_z). Since x, y, and z are principal axes, the components produce three separate equations:

$$\begin{aligned} h_x &= I_x\omega_x \\ h_y &= I_y\omega_y \\ h_z &= I_z\omega_z. \end{aligned} \tag{4}$$

There is mass symmetry about the z axis, so we can say

$$I_x = I_y. \tag{5}$$

If we consider a case where no torques are applied about the z axis, equation 2 reduces to

$$m_x = I_x p\omega_x + (I_z - I_x)\,\omega_z\omega_y \tag{6a}$$

$$m_y = I_x p\omega_y - (I_z - I_x)\,\omega_z\omega_x. \tag{6b}$$

If we assume that the rocket is spinning about the z axis at a constant rate (ω_z) and if the applied torques are known, then equations 6a and 6b are coupled, first order, differential equations. These coupled equations combine to give for the characteristic equation:

$$p^2\omega_x + (1 - I_z/I_x)^2\,\omega_z^2\omega_x = 0 \tag{7a}$$

$$p^2\omega_y + (1 - I_z/I_x)^2\omega_z^2\,\omega_y = 0. \tag{7b}$$

In the case of the meteorological rocket, I_x is much greater than I_z, so that equations 7a and 7b reduce to approximately

$$p^2\omega_x + \omega_z^2\,\omega_x = (p^2 + \omega_z^2)\,\omega_x = 0 \tag{7c}$$

$$p^2\omega_y + \omega_z^2\,\omega_y = (p^2 + \omega_z^2)\,\omega_y = 0. \tag{7d}$$

The solutions to these equations are

$$\omega_x = \omega_{x-y}\sin\omega_z t \tag{8a}$$

$$\omega_y = \omega_{x-y}\cos\omega_z t. \tag{8b}$$

The meaning of these equations might be reasoned physically. That is to say, most of the total angular velocity Ω is contained in component ω_z. The remaining angular velocity lies in the x-y plane, or

$$\Omega^2 = \omega_z^2 + \omega_{x-y}^2 = \omega_z^2 + \omega_x^2 + \omega_y^2. \tag{9}$$

Since axes x and y are rotating with the body, components ω_x and ω_y are oscillating sinusoidally with amplitudes ω_{x-y} as shown by equations 8a and 8b. Thus, twice during each revolution ω_x or ω_y becomes zero. At the instant ω_x or ω_y becomes zero, the moment equations 6a and 6b

become uncoupled. If a torque (m_y) is applied in an impulsive fashion each time ω_x is zero, the payload can be tilted to the horizontal.

SECTION 5 - DESCRIPTION OF A SIMPLE MODEL

The attitude control problem is to make the z axis of the payload coincide with the u axis of the trajectory as quickly as possible, and to make the payload maintain this attitude during the flight.

A simple two-degrees-of-freedom gyro can be used to maintain the u axis.

A bang-bang control jet (cold propellant) can be used to bring the z axis into line. The control jet could be discharged in an impulsive manner parallel to the x axis at distance r from the origin (see Fig. 2). The jet would be discharged once during each revolution when ω_x is zero. The integrated effect of all the impulsive torques are equivalent to a continuous torque (T).

The moment of inertia ratio (I_z/I_x) must be small (0.05 or less). The spin rate must also be small (on the order of 60 rpm). If the torquing impulse is spread over 1 radian during each revolution, the imparted angular momentum (h_y) may be large compared to the original angular momentum (h_z). If the impulses are applied strong enough and often enough, the torque may be considered continuous, so that Newton's Law of Angular Motion may apply without regard to small nutation and precession effects; therefore:

$$T = I_x p^2 \delta. \tag{10}$$

(Henceforth I_x will be referred to as I.)

It is apparent from equation 10 that if T is always applied in a direction to drive the z axis toward the u axis, the z axis will oscillate about the u axis but never settle on it. So the system must be damped by a torque (D) opposite to $p\delta$.

For a simplified case, the system would be linearized and critically damped. To do this, T would be made proportional to the δ, and D made proportional to $p\delta$.

δ can be measured by a reference to the attitude gyro. $p\delta$ can be measured by a linear z-axis acceleration, since the only significant z-axis acceleration in free fall will result from the centrifugal force produced by the angular velocity.

$$a_z = \left| p\delta \times (R \times p\delta) \right| = R\,(p\delta)^2. \tag{11}$$

That is, if a_z is measured by the accelerometer, then $p\delta$ is also determined.

To make T proportional to δ, and D proportional to $p\delta$, the pulse length or pulse strength must be modulated. This can be done simply only over a rather limited dynamic range.

The equation of motion with damping thus becomes

$$m_y = T + D = I\,p^2\,\delta. \tag{12}$$

It was specified that m_y is composed of T and D whose equivalents are

$$-T = k\delta \tag{13}$$

$$-D = fp\delta. \tag{14}$$

So that equation 12 becomes the familiar differential equation

$$Ip^2\delta + fp\delta + k\delta = 0. \tag{15}$$

Normalizing equation 15 gives

$$p^2\delta + (f/I)p\delta + (k/I)\delta = 0. \tag{16}$$

A critically damped condition is one in which there is no overshoot nor overdamping. It is determined by the condition that

$$f^2 = 4Ik. \tag{17}$$

Thus equation 15 becomes

$$p^2\delta + 2\sqrt{k/I}\,p\delta + (k/I)\delta = 0. \tag{18}$$

In practical engineering, it is easier to set up equations in terms of the undamped natural frequency (ω_n).

$$p^2\delta + 2\omega_n p\delta + \omega_n^2 \delta = 0 \tag{19}$$

where

$$\omega_n^2 = k/I. \tag{20}$$

To see if the above equations could be used to represent a workable system, it may be assumed that the vehicle would have a moment of inertia (I) of about 160 slug ft^2. This moment of inertia is about that of the Javelin vehicle which could be used as an intermediate meteorological rocket.

When the rocket leaves the atmosphere, its inclination angle (δ_0) will be about 1.2 radians.

For a first approximation, consider a critically damped case where it is desired to tilt from an initial angle of 70 degrees (i.e., δ_0 = 1.2 radians) to within 5 degrees of the horizontal in 35 sec. A standard engineering graph gives a value of ω_n of 1/8 radian per second.

From equation 20, k may be found:

$$k = I\omega_n^2 = (160)(1/8)^2 \text{ slug ft}^2 \text{ rad}^2 \text{ sec}^{-2} = 2.5 \text{ ft lb.} \tag{21}$$

From equation 17, f may be found to be 40 ft lb sec, i.e.,

$$f = \sqrt{4Ik} = \sqrt{4 \times 160 \times 2.5} = 40 \text{ ft lb sec.} \tag{22}$$

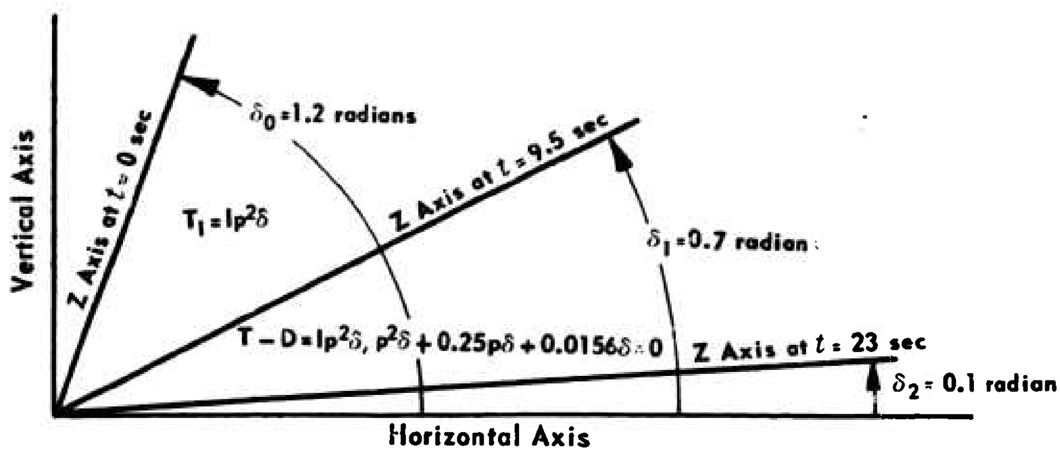

Fig. 5: History of δ.

The maximum torque which might be expected is

$$T_{max} = k\delta_{max} = 2.5 \text{ ft lb} \times 1.2 \text{ rad} = 3 \text{ ft lb.} \tag{23}$$

The maximum damping torque which might be expected is about

$$D_{max} = f(p\delta)_{max} = 40 \text{ ft lb sec} \times 0.1 \text{ rad/sec} = 4 \text{ ft lb.} \tag{24}$$

For the first approximation, the system was assumed to be characterized by a critically damped condition from the beginning.

As a second approximation, consider a more practical system that is initially undamped. When δ reaches a predetermined value ($\delta_1 = 0.7$ radian) damping begins (see Fig. 5).

The history of the torque (T) is shown as a function of δ in Fig. 6. Fig. 7 is a graph of the damping torque D. Fig. 8 contains complete graphical representation.

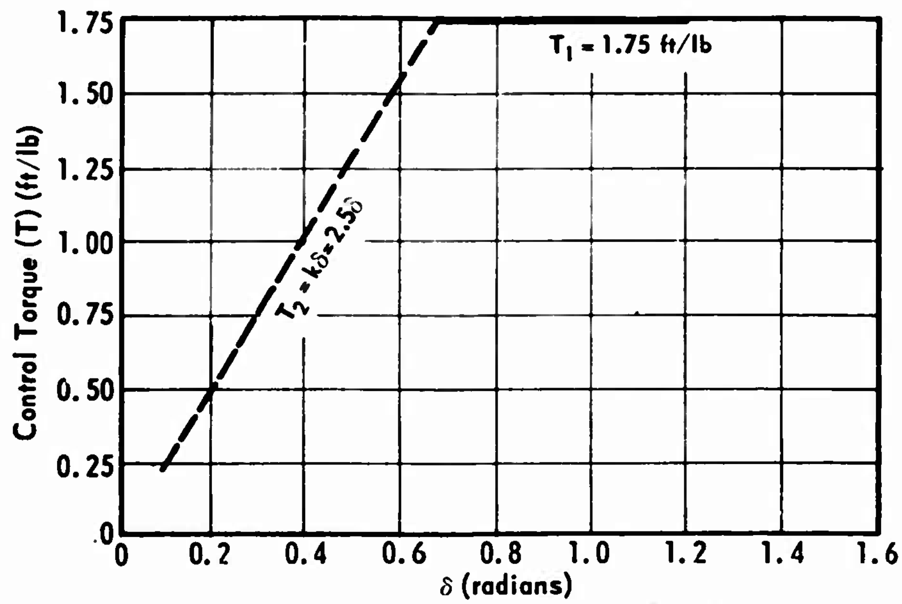

Fig. 6: Control Torque vs δ.

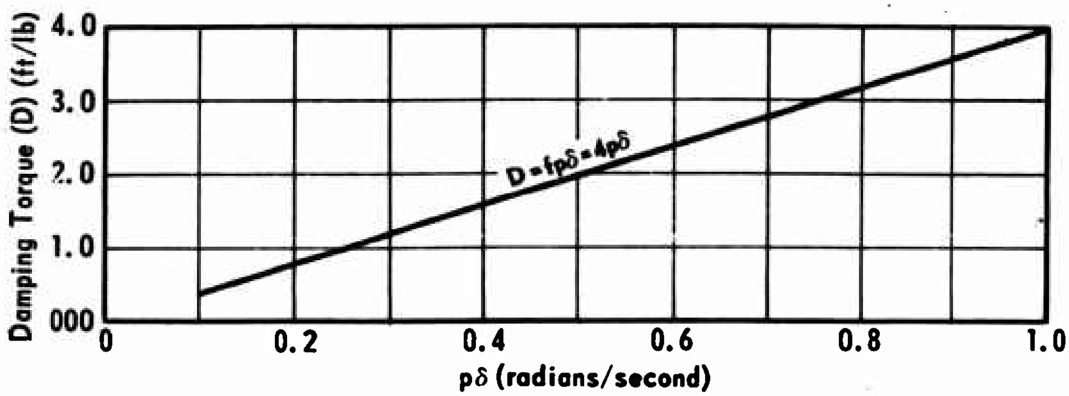

Fig. 7: Damping Torque vs pδ.

The mathematics of the system are as follows:

In the increment 0 to 1 (see Fig. 8), T is at saturation = $k\delta_1$ = 2.5 x 0.7 = 1.75 ft ›.

$$T_{0-1} = k\delta_1 = I(p^2\delta)_{0-1} = \text{saturation torque,} \tag{25}$$

so that the angular acceleration in the region is

$$(p^2\delta)_{0-1} = k\delta_1/I = 1.75 \text{ ft lb}/160 \text{ slug ft}^2 = 0.011 \text{ rad/sec}^2. \tag{26}$$

With this constant acceleration it takes 9.5 sec to go from δ_0 to δ_1,

$$\delta_1 - \delta_0 = \overline{(p\delta)}_{0-1}\, t = (\tfrac{1}{2})\,(p^2\delta)_{0-1}\, t^2 =$$

$$(0.0055 \text{ rad/sec}^2)\, t^2 = 0.5 \text{ rad} \tag{27}$$

$$t = 9.5 \text{ sec.} \tag{28}$$

At position δ_1, $p\delta_1$ will be maximum so that D will begin at a maximum of about 4 ft lb.

When the viscous damping* begins, the initial conditions are

$$\delta_1 = 0.7 \text{ rad} \tag{29}$$

$$p\delta_1 = -0.1 \text{ rad/sec.} \tag{30}$$

The differential equation which describes viscous damping phase is given by equation 16 and is numerically equal to

$$p^2\delta + 0.25\, p\delta + 0.0156\, \delta = 0. \tag{31}$$

**Viscous damping is defined as damping which is porportional to the rate of change.*

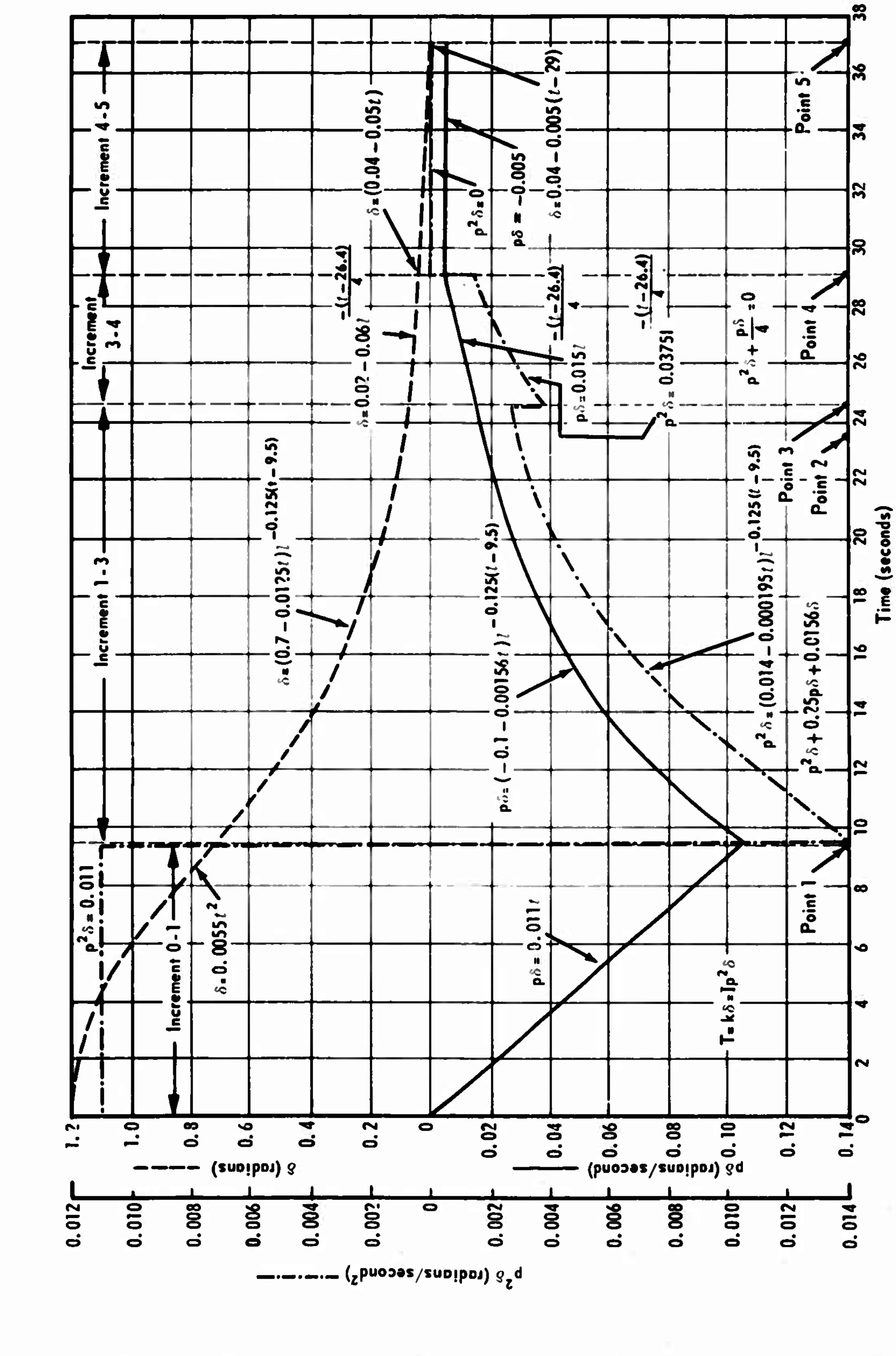

Fig. 8: History of Attitude Control Factors.

This differential equation, with the initial conditions specified by equations 29 and 30, can easily be solved by transforming into Laplacian space.

$$p^2\bar{\delta} + 0.25\, p\bar{\delta} + 0.0156\, \bar{\delta} = \delta_1 p + (p\delta)_1 + 0.25\delta_1 = 0.7p - 0.1 + 0.175. \quad (32)$$

It can be seen that the right side of Laplacian equation 32 expresses the initial conditions. Solving for $\bar{\delta}$ gives

$$\bar{\delta} = (0.7p + 0.075)/(p + 0.125)^2 \quad (33)$$

Transforming back into the time domain gives

$$\delta = [0.7 - 0.0125\,(t - 9.5)] \exp - [0.125\,(t - 9.5)]. \quad (34)$$

δ is shown in Fig. 8 as a function of time. From Fig. 8, it can be seen that δ reaches point 2 (δ_2 = 0.087 rad = 5°) 23.5 sec after thrusting begins.

As δ becomes small, so does $p\delta$, and so do T and D. Since the valve opening times will probably restrict T and D, consider the case where the minimum T and/or D is 0.2 ft lb. By the time this happens, δ_3 = 0.08 radian (or 4.5 degrees), which is within the 5-degree accuracy required.

At this point (point 3), it can be seen from Fig. 8 that $p\delta_3$ is -0.015 rad/sec. At this point, T must cut off so that only the damping torque remains. So in the increment 3 to 4, equation 31 reduces to

$$p^2\delta + 0.25\, p\delta + 0 = 0. \quad (35)$$

Thus δ_3 = 0.08 radian and $p\delta_3$ = -0.015 rad/sec are the initial conditions of the increment. The boundary condition is that D_4 = 0.2 ft lb. D = 0.2 ft lb gives an acceleration at δ_4 of $p^2\delta_4 = -0.00125$ rad/sec^2, which is equivalent to an angular velocity of $p\delta_4 = -0.005$ rad/sec.

The solution may be found by the Laplace transformation

$$p^2\bar{\delta} + 0.25\, p\bar{\delta} = \text{initial conditions} = \delta_3 p + p\delta_3 + \delta_3 \quad (36)$$

to be

$$\delta_{3-4} = 0.02 + 0.06 \exp (24.6 - t)/4 \quad (37)$$

in the increment 3 to 4.

δ_4 is that point at which D = 0.2 ft lb. This is found to occur at t = 29 sec. This can be found by differentiating equation 37 and using the boundary condition $p\delta_4 = -0.005$ rad/sec, .

$$p\delta_4 = -0.005 = -0.015 \exp [(24.6 - t)/4] \tag{38}$$

$$t = (4 \ln 3) + 24.6 = 29 \text{ sec} \tag{39}$$

so that

$$\delta_4 = 0.02 + 0.06 \exp (24.6 - t)/4 = 0.04 \text{ rad.} \tag{40}$$

By the time D and T reach their minimum values, the attitude of the vehicle is well within the desired limits. From this point on, T and D can be programed in a simple manner to keep within the 5-degree limits. For example, T and D can be given constant values and applied in a manner to add, subtract, or be zero by a simple decision circuit based on whether δ times $p\delta$ is negative or positive. The proof of this method was shown by Dr. R. M. Howe.*

SECTION 6 - CONCLUSIONS

In order to control the attitude of a meteorological rocket in the manner proposed, the longitudinal angular momentum should be great enough for stability, but small as compared to the lateral angular momentum imparted by the control torque. The torque could be applied by a cold propellant discharged by a bang-bang servo mechanism. The maximum thrust of the jet that would be required might be about 2.0 lb if the jet were placed 65 in. in front of the center of mass.

Based on the results of this study, it appears that the design and manufacture of a low cost attitude control system for a meteorological rocket is practical.

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* *Development and Test of a Simple Attitude Control System for Small Rockets, Department of Aeronautical and Astronautical Engineering, University of Michigan Research Institute, Ann Arbor, Michigan, November 1960.*

Air Proving Ground Center, Eglin Air Force Base, Florida
Rpt. No. APGC-TDR-62-30. ATTITUDE CONTROL FOR A METEOROLOGICAL ROCKET. Final report, July 1962, 17 p. incl. illus
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Air Proving Ground Center, Eglin Air Force Base, Florida
Rpt. No. APGC-TDR-62-30. ATTITUDE CONTROL FOR A METEOROLOGICAL ROCKET. Final report, July 1962. 17 p. incl. illus
Unclassified Report

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